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**Yamakaji**

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(54) **ELECTRODE MATERIAL AND METHOD  
FOR FORMING ELECTRODE MATERIAL**

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**H01M 4/5825** (2013.01); **H01M 4/625**  
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**60/122** (2013.01); **Y02T 10/7011** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,910,382 A 6/1999 Goodenough et al.  
6,085,015 A 7/2000 Armand et al.

(Continued)

FOREIGN PATENT DOCUMENTS

CN 101399336 A 4/2009  
CN 101465426 A 6/2009

(Continued)

OTHER PUBLICATIONS

Liang et al., Lithium iron phosphate with high-rate capability syn-  
thesized through hydrothermal reaction in glucose solution, 2008, J.  
Power Sources, 184, 538-542.\*

(Continued)

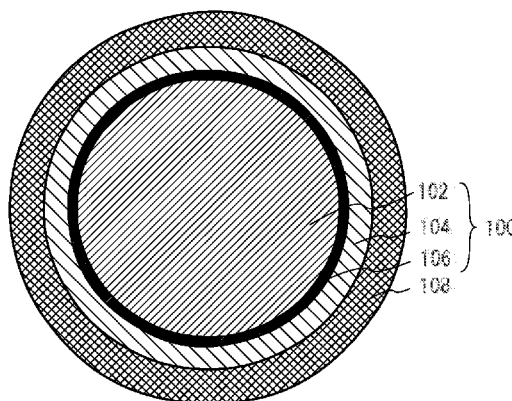
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(57) **ABSTRACT**

An object is to provide an electrode material with high elec-  
trical conductivity and a power storage device using the elec-  
trode material. An object is to provide an electrode material  
with high capacity and a power storage device using the  
electrode material. Provided is a particulate electrode mate-  
rial including a core containing a compound represented by a  
general formula  $\text{Li}_2\text{MSiO}_4$  (in the formula, M represents at  
least one kind of an element selected from Fe, Co, Mn, and  
Ni) as a main component, and a covering layer containing a  
compound represented by a general formula  $\text{LiMPO}_4$  as a  
main component and covering the core. Further, a solid solu-  
tion material is provided between the core and the covering  
layer. With such a structure, an electrode material with high  
electrical conductivity can be obtained. Further, with such an  
electrode material, a power storage device with high dis-  
charge capacity can be obtained.

**18 Claims, 7 Drawing Sheets**



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JP 2007-335325 12/2007  
 JP 2009-087682 A 4/2009  
 JP 2009-170401 A 7/2009  
 JP 2009-295533 A 12/2009  
 JP 2010-086772 A 4/2010  
 JP 2012-048865 A 3/2012  
 JP 2013-504858 2/2013  
 WO WO 2006/027925 A2 3/2006  
 WO WO 2009142283 A1 \* 11/2009

## (56)

**References Cited**

## U.S. PATENT DOCUMENTS

6,391,493 B1 5/2002 Goodenough et al.  
 6,514,640 B1 2/2003 Armand et al.  
 7,718,314 B2 5/2010 Komiyama et al.  
 8,586,182 B2 11/2013 Suzuki et al.  
 8,821,763 B2 9/2014 Sano et al.  
 2004/0096743 A1 5/2004 Okae et al.  
 2007/0202407 A1 8/2007 Eberman et al.  
 2008/0248382 A1 10/2008 Sastry et al.  
 2008/0268339 A1 10/2008 Suzuki  
 2009/0087660 A1 \* 4/2009 Suzuki et al. .... 428/403  
 2010/0078591 A1 \* 4/2010 Sano et al. .... 252/182.1  
 2010/0104943 A1 4/2010 Thomas et al.  
 2010/0140540 A1 6/2010 Yamada et al.  
 2010/0163790 A1 7/2010 Ceder et al.  
 2011/0068293 A1 \* 3/2011 Fujino et al. .... 252/182.1  
 2011/0269023 A1 11/2011 Kawakami et al.  
 2011/0291055 A1 12/2011 Kojima et al.  
 2011/0294009 A1 12/2011 Kawakami et al.  
 2011/0300441 A1 12/2011 Kawakami  
 2012/0237833 A1 9/2012 Guerfi et al.

## FOREIGN PATENT DOCUMENTS

EP 2043183 A 4/2009  
 JP 07-235292 A 9/1995  
 JP 11-025983 1/1999  
 JP 2002-075368 3/2002  
 JP 2007-103339 4/2007

## OTHER PUBLICATIONS

Zhou et al., "The Li intercalation potential of  $\text{LiMPO}_4$   $\text{LiMSiO}_4$  olivines with  $M = \text{Fe, Mn, Co, Ni}$ ", *Electrochemistry Communications*, Nov. 1, 2004, vol. 6, No. 11, pp. 1144-1148.  
 Kang et al., "Battery materials for ultrafast charging and discharging", *Nature*, Mar. 12, 2009, vol. 458, No. 12, pp. 190-193.  
 Nytén A. et al., "The lithium extraction/insertion mechanism in  $\text{Li}_2\text{FeSiO}_4$ ", *J. Mater. Chem.*, 2006, 16(23), 2266-2272.  
 Sirisopanaporn C. et al., "Dependence of  $\text{Li}_2\text{FeSiO}_4$  Electrochemistry on Structure", *J. Am. Chem. Soc.*, 2011, 133(5), 1263-1265.  
 Dominko R. et al., "In-situ XAS study on  $\text{Li}_2\text{MnSiO}_4$  and  $\text{Li}_2\text{FeSiO}_4$  cathode materials", *Journal of Power Sources*, 2009, 189(1), 51-58.  
 Chinese Office Action (Application No. 201110189756.1) Dated Aug. 1, 2014.  
 Philip W. Goetz et al., "The New Encyclopaedia Britannica, 15th Edition", vol. 10, p. 945.  
 Notification (Application No. 2011-143409) Dated Feb. 17, 2015.  
 Information Offer Form (Application No. 2011-143409) Dated Feb. 9, 2015.  
 Information Offer Form (Application No. 2011-143409) Dated Feb. 2, 2015.  
 Notification (Application No. 2011-143409) Dated Feb. 10, 2015.  
 Chinese Office Action (Application No. 201110189756.1) Dated Mar. 26, 2015.

\* cited by examiner

FIG. 1A

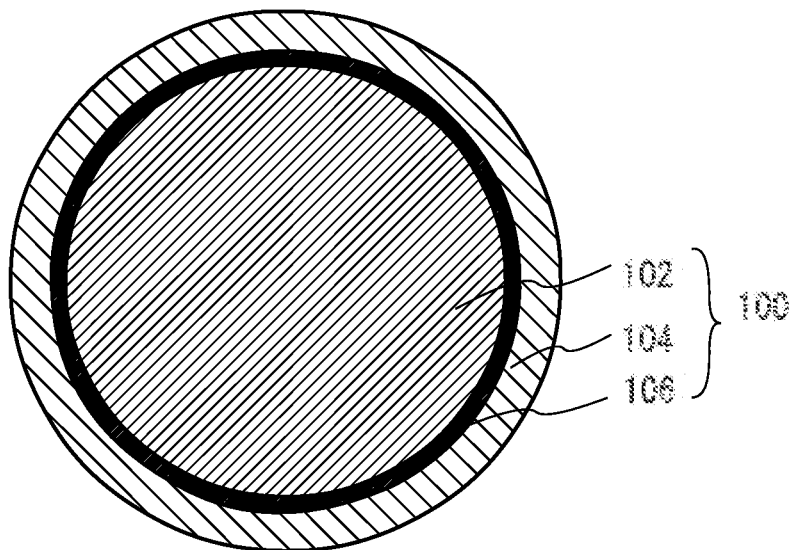


FIG. 1B

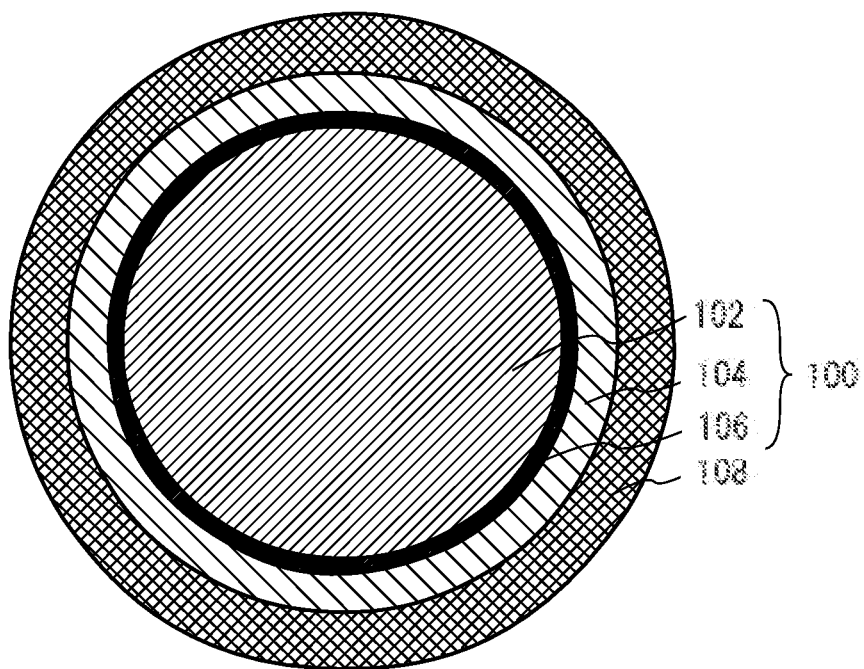


FIG. 2

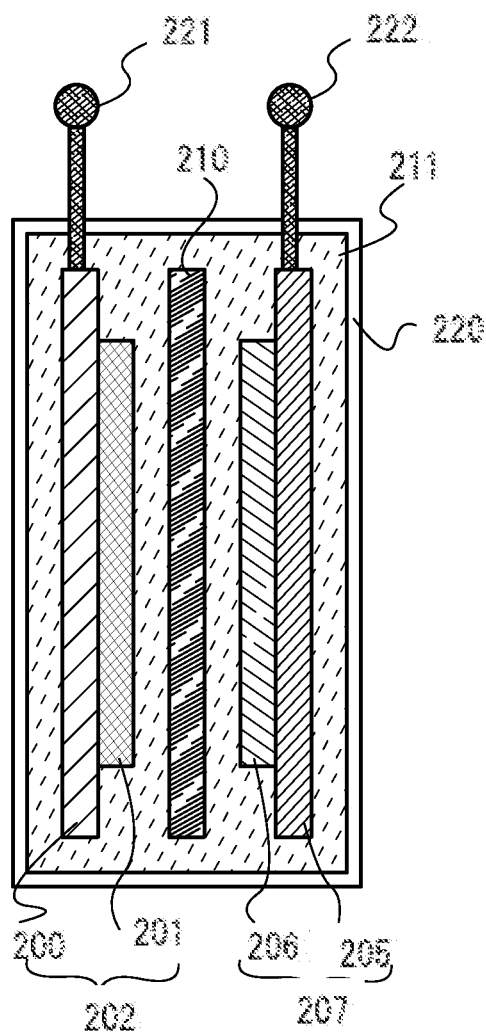


FIG. 3A

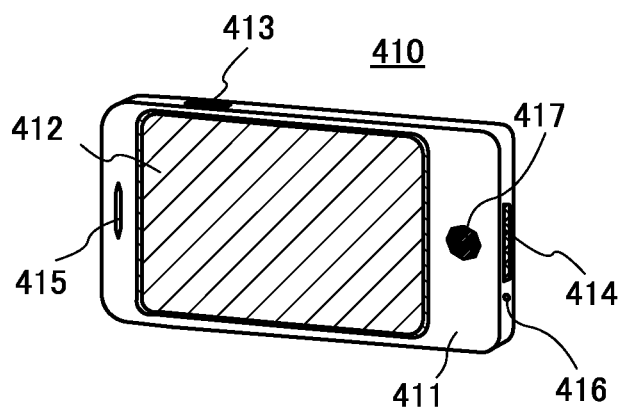


FIG. 3B

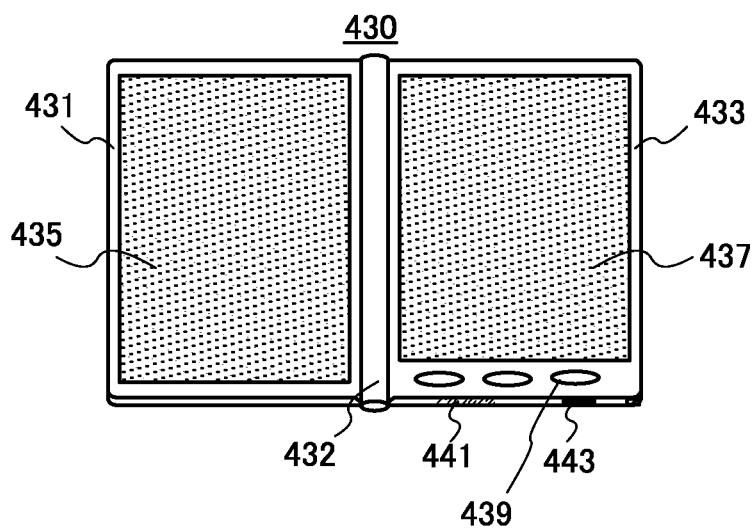


FIG. 4

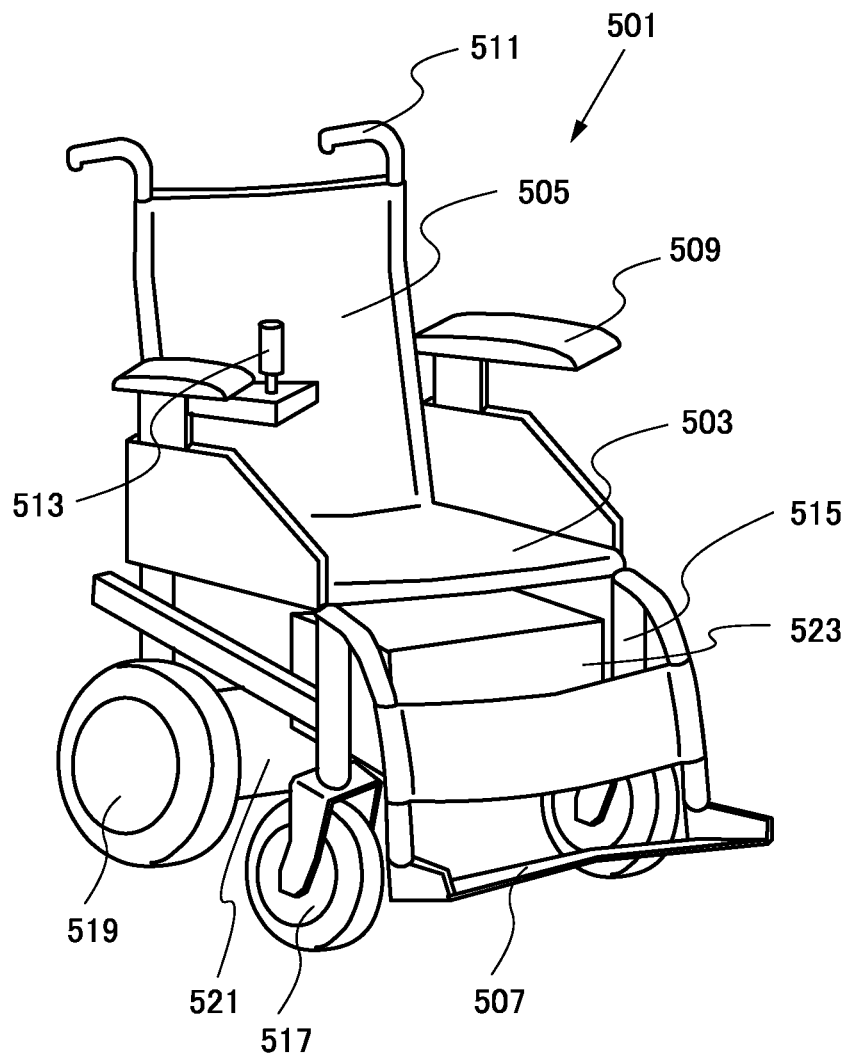


FIG. 5

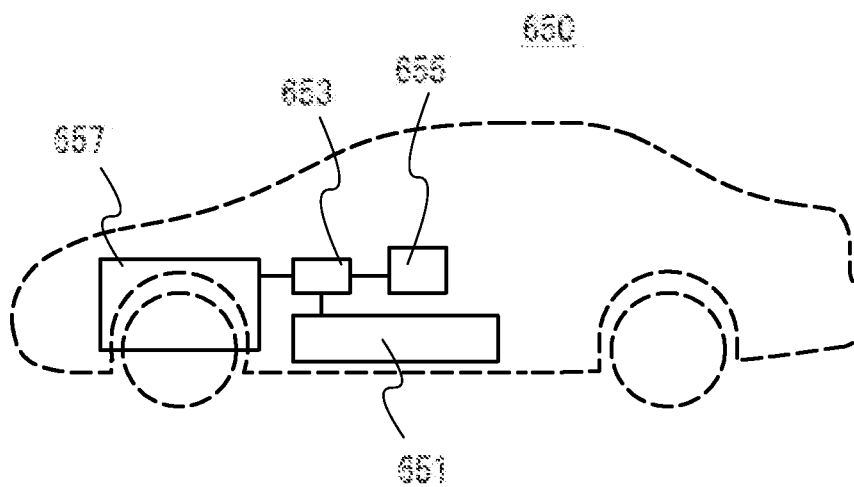


FIG. 6

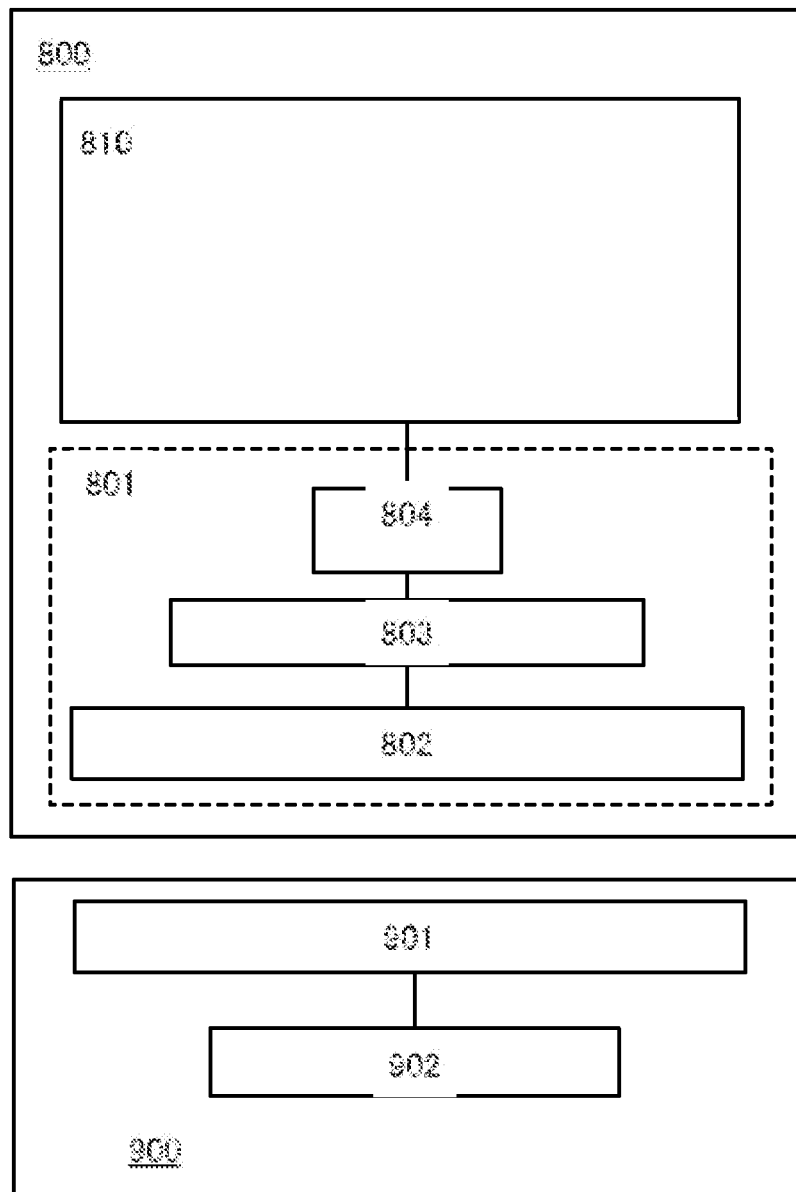
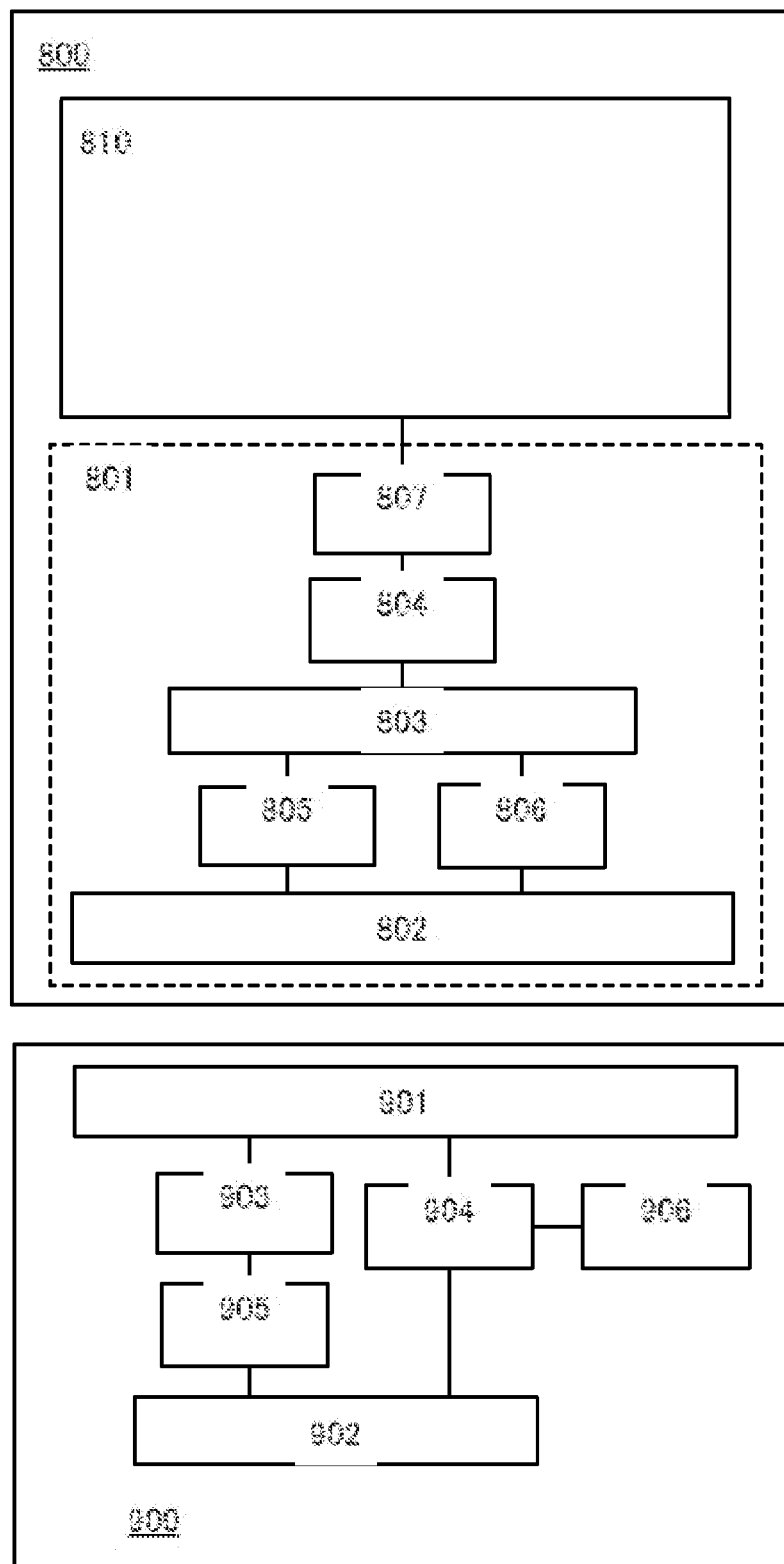




FIG. 7



# ELECTRODE MATERIAL AND METHOD FOR FORMING ELECTRODE MATERIAL

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention relates to an electrode material and a method for forming the electrode material.

### 2. Description of the Related Art

The field of portable electronic devices such as personal computers and cellular phones has progressed significantly. The portable electronic device needs a chargeable power storage device having high energy density, which is small, lightweight, and reliable. As such a power storage device, for example, a lithium-ion secondary battery is known. In addition, development of electrically propelled vehicles on which secondary batteries are mounted has also been progressing rapidly from a rise of growing awareness to environmental problems and energy problems.

In a lithium-ion secondary battery, as a positive electrode active material, a phosphate compound having an olivine structure and containing lithium (Li) and iron (Fe), manganese (Mn), cobalt (Co), or nickel (Ni), such as lithium iron phosphate ( $\text{LiFePO}_4$ ), lithium manganese phosphate ( $\text{LiMnPO}_4$ ), lithium cobalt phosphate ( $\text{LiCoPO}_4$ ), or lithium nickel phosphate ( $\text{LiNiPO}_4$ ), has been known (see Patent Document 1, Non-Patent Document 1, and Non-Patent Document 2).

Further, it is proposed that a silicate-based (silicate salt) compound having the same olivine structure as the phosphate compound having an olivine structure be used as a positive electrode active material of a lithium-ion secondary battery (for example, Patent Document 2). Furthermore, in Patent Document 2, a method for increasing conductivity of a positive electrode active material by including a carbon component in the positive electrode active material is disclosed.

## REFERENCE

### Patent Documents

[Patent Document 1] Japanese Published Patent Application No. H11-25983

[Patent Document 2] Japanese Published Patent Application No. 2007-335325

### Non-Patent Documents

[Non-Patent Document 1] Byoungwoo Kang, Gerbrand Ceder, "Nature", 2009, Vol. 458 (12), pp. 190-193

[Non-Patent Document 2] F. Zhou et al., "Electrochemistry Communications", 2004, Vol. 6, pp. 1144-1148

## SUMMARY OF THE INVENTION

However, the bulk electrical conductivity of a phosphate compound having an olivine structure or a silicate salt compound having an olivine structure is low, and it is difficult for a single particle to obtain characteristics sufficient for use as an electrode material.

In view of the foregoing problem, one of objects of the disclosed invention is to provide an electrode material with improved electrical conductivity and a power storage device using the electrode material in one embodiment of the disclosed invention.

Further, one of objects is to provide an electrode material with high capacity and a power storage device using the electrode material in one embodiment of the disclosed invention.

One embodiment of the present invention is an electrode material and a method for forming an electrode material. Details thereof will be described below.

One embodiment of the present invention is a particulate electrode material including a core containing a compound represented by a general formula  $\text{Li}_2\text{MSiO}_4$  (in the formula, M represents at least one kind of an element selected from Fe, Co, Mn, and Ni) as a main component, and a covering layer containing a compound represented by a general formula  $\text{LiMPO}_4$  as a main component and covering the core.

M included in the general formula  $\text{Li}_2\text{MSiO}_4$  may be different from or the same as M included in the general formula  $\text{LiMPO}_4$ . Further, it is preferable that the compound represented by the general formula  $\text{LiMPO}_4$  have high conductivity as compared to the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$ .

In the structure, a solid solution material is preferably provided between the core and the covering layer.

In the structure, a carbon coat layer which covers the covering layer is preferably provided. In the structure, the carbon coat layer preferably has a thickness of greater than 0 nm and less than or equal to 100 nm.

In the structure, the particle preferably has a grain diameter of greater than or equal to 10 nm and less than or equal to 100 nm.

In the structure, the weight of the core is preferably heavier than the weight of the covering layer.

In accordance with one embodiment of the present invention, an electrode material with high electrical conductivity can be obtained. Further, with such an electrode material, a power storage device with high discharge capacity can be obtained.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIGS. 1A and 1B are cross-sectional views of positive electrode active materials (in particle form);

FIG. 2 illustrates one example of a cross-sectional view of a power storage device;

FIGS. 3A and 3B are diagrams each illustrating an application example of a power storage device;

FIG. 4 is a perspective view illustrating an application example of a power storage device;

FIG. 5 is a diagram illustrating an application example of a power storage device;

FIG. 6 is a diagram illustrating an example of a configuration of a wireless power feeding system; and

FIG. 7 is a diagram illustrating an example of a configuration of a wireless power feeding system.

## DETAILED DESCRIPTION OF THE INVENTION

Hereinafter, embodiments are described in detail with reference to the drawings. Note that the invention is not limited to the following description of the embodiments, and it is readily appreciated by those skilled in the art that modes and details of the invention can be modified in a variety of ways without departing from the spirit of the invention disclosed in this specification and the like. Structures of different embodiments can be implemented in combination as appropriate. Note that in structures of the invention described below, the same portions or portions having similar functions are denoted by common reference numerals, and detailed description thereof will be omitted.

Note that the position, the size, the range, or the like of each structure illustrated in the drawings and the like is not accu-

rately represented in some cases for easy understanding. Therefore, the present invention is not necessarily limited to the position, size, range, or the like disclosed in the drawings and the like.

Note that terms with ordinal numbers such as “first”, “second”, and “third” in this specification are used in order to identify components, and the terms do not limit the components numerically.

#### Embodiment 1

In this embodiment, a structure of an electrode material which is one embodiment of the present invention will be described with reference to FIGS. 1A and 1B.

FIG. 1A is a schematic cross-sectional view of a positive electrode active material **100** which is one embodiment of the present invention.

The positive electrode active material **100** is in particle form, and a positive electrode active material layer which is described later is formed using a plurality of positive electrode active materials **100** in particle form.

As shown in FIG. 1A, the positive electrode active material **100** includes a core **102** containing a compound represented by a general formula  $\text{Li}_2\text{MSiO}_4$  (in the formula, M represents at least one kind of an element selected from Fe, Co, Mn, and Ni) as a main component, and a covering layer **104** containing a compound represented by a general formula  $\text{LiMPO}_4$  as a main component and covering the core **102**. Further, a solid solution material **106** exists between the core **102** and the covering layer **104**. In the solid solution material **106**, a slight amount of the compound represented by the general formula  $\text{LiMPO}_4$  is dissolved in the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$ . In the solid solution material **106**, about 10% of the compound represented by the general formula  $\text{LiMPO}_4$  is preferably dissolved in the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$ .

As illustrated in FIG. 1A, the solid solution material **106** exists between the core **102** containing the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$  as a main component and the covering layer **104** containing the compound represented by the general formula  $\text{LiMPO}_4$  as a main component. Thus, an energy barrier when Li in the general formula  $\text{Li}_2\text{MSiO}_4$  is inserted into and extracted from the surface of the positive electrode active material **100** can be decreased. As a result, the positive electrode active material **100** makes it possible to bring the available capacity close to the theoretical capacity. Further, electrical conductivity of the positive electrode active material **100** can be improved.

The positive electrode active material **100** has a core-shell structure. The core-shell structure is a structure in which one of two chemical species forms a core, and the other of the two chemical species covers the core like a shell. With such a structure, the core can be made stable by the covering layer **104**, the covering layer **104** can have high functionality by the core **102**, and characteristics of the core **102** and the covering layer **104** can be concurrently used. That is to say, the core **102** includes the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$ , whereby 2 mol of Li is included in 1 mol of a transition metal; thus, the positive electrode active material **100** can be used as an electrode material with high capacity. Further, the core **102** is covered with the compound represented by  $\text{LiMPO}_4$  with higher electric conductivity than the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$ , whereby an electrode material with high capacity and high electric conductivity (the positive electrode active material **100**) can be formed.

The positive electrode active material **100** illustrated in FIG. 1B includes the core **102** containing the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$  as a main component, and the covering layer **104** containing the compound represented by the general formula  $\text{LiMPO}_4$  as a main component and covering the core **102**. Further, the covering layer **104** is covered with a carbon coat layer **108**. Furthermore, the solid solution material **106** exists between the core **102** and the covering layer **104**.

With the carbon coat layer **108** provided on the surface of the covering layer **104** as illustrated in FIG. 1B, the conductivity of the positive electrode active material **100** can be improved. Further, when the positive electrode active materials **100** are in contact with each other through the carbon coat layers **108**, the positive electrode active materials **100** are electrically connected to each other, whereby the electric conductivity of the positive electrode active material **100** can be further improved.

Next, an example of a method for forming the electrode material (the positive electrode active material **100**) which is one embodiment of the present invention is described.

First, an example of a method for forming the core **102** containing the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$  is described.

First, a solution is added to a compound to be a supply source of Li, a compound to be a supply source of M, and a compound to be a supply source of Si in the general formula, and mixture is performed; thus, a mixture material is formed. M in the general formula represents, for example, one or more of elements selected from iron (Fe), manganese (Mn), cobalt (Co), nickel (Ni), and the like.

As the compound to be a supply source of Li in the general formula, for example, lithium salt such as lithium carbonate ( $\text{Li}_2\text{CO}_3$ ), lithium oxide ( $\text{Li}_2\text{O}$ ), lithium sulfide ( $\text{Li}_2\text{S}$ ), lithium peroxide ( $\text{Li}_2\text{O}_2$ ), lithium sulfate ( $\text{Li}_2\text{SO}_4$ ), lithium sulfite ( $\text{Li}_2\text{SO}_3$ ), or lithium thiosulfate ( $\text{Li}_2\text{S}_2\text{O}_3$ ) can be used.

As the compound to be a supply source of M in the general formula, for example, an oxide such as iron(II) oxide ( $\text{FeO}$ ), manganese(II) oxide ( $\text{MnO}$ ), cobalt(II) oxide ( $\text{CoO}$ ), or nickel(II) oxide ( $\text{NiO}$ ), or an oxalate such as iron(II) oxalate dehydrate ( $\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ ), manganese(II) oxalate dehydrate ( $\text{MnC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ ), cobalt(II) oxalate dehydrate ( $\text{CoC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ ), or nickel(II) oxalate dehydrate ( $\text{NiC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ ) can be used.

As the compound to be a supply source of Si in the general formula, for example, silicon oxide ( $\text{SiO}_2$ ) can be used.

Further, lithium metasilicate ( $\text{Li}_2\text{SiO}_3$ ) can be used as a raw material for introducing lithium and silicate.

Next, a solvent is added to the compound to be a supply source of Li, the compound to be a supply source of M, and the compound to be a supply source of Si in the general formula, and mixture is performed; thus, a mixture material is formed.

As a method for mixing the compound to be a supply source of Li, the compound to be a supply source of M, and the compound to be a supply source of Si in the general formula, a ball mill treatment can be used, for example. A specific method is as follows. A solvent such as acetone which is highly volatile is added to the compounds, and with the use of a ball (having a ball diameter of greater than or equal to  $\phi 1$  mm and less than or equal to  $\phi 10$  mm) made of metal or ceramic, treatment is performed at greater than or equal to 50 rpm and less than or equal to 500 rpm for greater than or equal to 30 minutes and less than or equal to 5 hours. By performing a ball mill treatment, the compounds can be microparticulated as well as being mixed, so that  $\text{Li}_2\text{MSiO}_4$  after formation can be microparticulated. In addition, by performing a ball mill

5

treatment, the compounds can be uniformly mixed and the crystallinity of the electrode material after formation can be made high. Although acetone is used as the solvent, ethanol, methanol, or the like can also be used.

For example, a ball mill treatment may be performed as follows: lithium metasilicate is used as the compound to be a supply source of Li and the compound to be a supply source of Si in the general formula, and iron(II) oxalate dehydrate is used as the compound to be a supply source of M in the general formula, and acetone is added as the solvent.

Subsequently, the mixture material is heated, so that the solvent (acetone) is evaporated. Then, pressure is applied to the mixture material with the use of a pellet press, so that the mixture material is shaped into pellets. The pellets are subjected to first heat treatment (pre-baking).

For example, the mixture material of the compounds (lithium metasilicate and iron(II) oxalate dehydrate) subjected to the ball mill treatment is heated to 50° C., so that the solvent (acetone) is evaporated. Then, pressure of 14.7 Pa (150 kgf/cm<sup>2</sup>) is applied to the mixture material with the use of a pellet press for 5 minutes, so that the mixture material is shaped into pellets. Then, the mixture shaped into pellets is subjected to first heat treatment (pre-baking) under a nitrogen atmosphere.

The first heat treatment may be performed at higher than or equal to 250° C. and lower than or equal to 450° C., preferably lower than or equal to 400° C., for greater than or equal to 1 hour and less than or equal to 20 hours, preferably less than or equal to 10 hours. In this embodiment, the first heat treatment is performed at a baking temperature of 350° C. for 10 hours. By the first heat treatment (pre-baking) at a low temperature of less than or equal to 400° C., iron(II) oxalate dehydrate can be changed into iron(II) oxide.

In order to prevent oxidation of M in the general formula, the first heat treatment may be performed under an inert gas atmosphere. For example, as the inert gas atmosphere, nitrogen, a rare gas (helium, neon, argon, xenon, or the like), or the like can be used. Alternatively, the first heat treatment may be performed under a hydrogen atmosphere.

Next, the mixture material subjected to the first heat treatment is ground with the use of a mortar or the like, and the mixture material is shaped into pellets again. The pellets are subjected to second heat treatment (main baking).

The second heat treatment can be performed, for example, under an inert gas atmosphere at a baking temperature of higher than or equal to 700° C. and lower than or equal to 800° C. for greater than or equal to 1 hour and less than or equal to 20 hours. The second heat treatment can be performed, for example, under a nitrogen atmosphere at a baking temperature of 700° C. for 10 hours. By the second heat treatment, a core of the electrode material which is microparticulated can be formed.

Through the above steps, the core **102** containing the compound represented by Li<sub>2</sub>MSiO<sub>4</sub> can be formed.

Next, an example of a method for forming the covering layer **104** containing the compound represented by LiMPO<sub>4</sub> and covering the core **102** is described.

First, a solution is added to a compound to be a supply source of Li, a compound to be a supply source of M, and a compound to be a supply source of PO<sub>4</sub> in the general formula, and mixture is performed; thus, a mixture material is formed. M in the general formula represents, for example, one or more of elements selected from iron (Fe), manganese (Mn), cobalt (Co), nickel (Ni), and the like.

Since the compound to be a supply source of Li and the compound to be a supply source of M in the general formula can be formed using the materials described in the method for

6

forming Li<sub>2</sub>MSiO<sub>4</sub>, the detailed description is omitted. Further, M included in the general formula Li<sub>2</sub>MSiO<sub>4</sub> may be different from or the same as M included in the general formula LiMPO<sub>4</sub>.

As the compound to be a supply source of PO<sub>4</sub> in the general formula, for example, diammonium hydrogen phosphate ((NH<sub>4</sub>)<sub>2</sub>HPO<sub>4</sub>), ammonium dihydrogen phosphate (NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub>), or phosphorus pentoxide (P<sub>2</sub>O<sub>5</sub>) can be used.

First, the compound represented by Li<sub>2</sub>MSiO<sub>4</sub> is ground with the use of a mortar or the like. Then, a solvent is added to the compound to be a supply source of Li, the compound to be a supply source of M, and the compound to be a supply source of PO<sub>4</sub> in the general formula, and mixture is performed; thus, the mixture material is formed.

As a method for mixing the compound to be a supply source of Li, the compound to be a supply source of M, and the compound to be a supply source of PO<sub>4</sub> in the general formula, a ball mill treatment may be performed. The detailed description of a specific method of a ball mill treatment is omitted because the method described in the method for forming Li<sub>2</sub>MSiO<sub>4</sub> can be applied thereto. By performing a ball mill treatment, the compounds can be microparticulated as well as being mixed.

For example, a ball mill treatment may be performed as follows: Li<sub>2</sub>CO<sub>3</sub> is used as the compound to be a supply source of Li, FeC<sub>2</sub>O<sub>4</sub>·2H<sub>2</sub>O is used as the compound to be a supply source of M, and NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub> is used as the compound to be a supply source of PO<sub>4</sub>, and acetone is added as the solvent.

Subsequently, the mixture material is heated, so that the solvent (acetone) is evaporated. Then, pressure is applied to the mixture material with the use of a pellet press, so that the mixture material is shaped into pellets. The pellets are subjected to third heat treatment (pre-baking).

For example, the mixture material of the compounds (Li<sub>2</sub>CO<sub>3</sub>, FeC<sub>2</sub>O<sub>4</sub>·2H<sub>2</sub>O, and NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub>) subjected to the ball mill treatment is heated to 50° C., so that the solvent (acetone) is evaporated. Then, pressure of 14.7 Pa (150 kgf/cm<sup>2</sup>) is applied to the mixture material with the use of a pellet press for 5 minutes, so that the mixture material is shaped into pellets. Then, the mixture shaped into pellets is subjected to the third heat treatment (pre-baking) under a nitrogen atmosphere at a baking temperature of 350° C. for 10 hours. By performing the third heat treatment, the core **102** containing the compound represented by the general formula Li<sub>2</sub>MSiO<sub>4</sub> and the covering layer **104** containing the compound represented by the general formula LiMPO<sub>4</sub> and covering the core **102** can be formed. For example, Li<sub>2</sub>FeSiO<sub>4</sub> can be formed as the core **102**, and LiFePO<sub>4</sub> can be formed as the covering layer **104**. The weight of the core **102** is heavier than the weight of the covering layer **104**.

Next, fourth heat treatment (main baking) is performed at a high temperature (600° C.). By performing the fourth heat treatment, elements included in the core **102** (e.g., Li<sub>2</sub>FeSiO<sub>4</sub>) and the covering layer **104** (e.g., LiFePO<sub>4</sub>) are diffused into the core **102** and the covering layer **104**, so that the solid solution material **106** in which the boundary between the core **102** and the covering layer **104** is unclear is formed. By formation of the solid solution material **106**, the structure shown in FIGS. 1A and 1B (the positive electrode active material **100**) can be formed. When such a solid solution material **106** exists, Li included in the core **102** is easily and effectively inserted and extracted as compared to the case where the solid solution material **106** does not exist. Further, by performing the fourth heat treatment, the crystallinity of LiMPO<sub>4</sub> can be increased. By increase of the crystallinity of LiMPO<sub>4</sub>, Li can be inserted and extracted more easily.

Note that in the fourth heat treatment, an organic compound such as glucose may be added. When the subsequent steps are performed after glucose is added, carbon supplied from the glucose is supported on the surface of the positive electrode active material (see FIG. 1B).

Note that in this specification, a state in which a surface of the covering layer **104** is supported with carbon also means that an iron phosphate compound is carbon-coated.

The thickness of the carbon with which the surface of the covering layer **104** is supported (also referred to as the carbon coat layer **108**) is greater than 0 nm and less than or equal to 100 nm, preferably greater than or equal to 2 nm and less than or equal to 10 nm.

By supporting carbon on the surface of the covering layer **104**, the conductivity of the surface of the positive electrode active material **100** can be increased. In addition, when the positive electrode active materials **100** are in contact with each other through carbon supported on the surfaces, the positive electrode active materials **100** are electrically connected to each other; thus, the conductivity of the positive electrode active material **100** can be further increased.

If the carbon coat layer **108** is formed on the core **102**, the core **102** might be reduced. However, by formation of the covering layer **104** on the core **102** as in one embodiment of the present invention, the reduction of the core **102** by the carbon coat layer **108** can be suppressed.

Note that although glucose is used in this embodiment as a carbon supply source because glucose easily reacts with a phosphate group included in the covering layer **104**, cyclic monosaccharide, straight-chain monosaccharide, or polysaccharide which reacts well with a phosphate group may be used instead of glucose.

Note that although an example in which an organic compound is added in the fourth heat treatment is described in this embodiment, one embodiment of the present invention is not limited thereto. An organic compound may be added after fifth heat treatment to form the carbon coat layer **108**.

The grain size of the particle of the positive electrode active material **100**, which is obtained through the fourth heat treatment, is greater than or equal to 10 nm and less than or equal to 100 nm, preferably greater than or equal to 20 nm and less than or equal to 60 nm. The particle of the positive electrode active material **100** is small when the grain size of the particle of the positive electrode active material **100** is within the above range; therefore, lithium ions are easily inserted and extracted. Thus, rate characteristics of a power storage device are improved and charge and discharge can be performed in a short time.

The baking temperature of  $\text{Li}_2\text{MSiO}_4$  is higher than the baking temperature of  $\text{LiMPO}_4$  by 100° C. or more. Therefore, the thickness of the solid solution material **106** can be made thin.

As a formation method of the core **102**, a sol-gel method, a hydrothermal method, a coprecipitation method, a spray drying method, or the like may be used instead of the method described in this embodiment. Further, as a formation method of the covering layer **104**, a sputtering method, a CVD method, a sol-gel method, a hydrothermal method, a coprecipitation method, or the like may be used instead of the method described in this embodiment.

This embodiment can be combined with any other embodiment.

#### Embodiment 2

In this embodiment, a lithium-ion secondary battery in which an electrode material obtained by the formation steps

described in Embodiment 1 is used as a positive electrode active material is described. The schematic structure of the lithium-ion secondary battery is illustrated in FIG. 2.

In the lithium-ion secondary battery illustrated in FIG. 2, a positive electrode **202**, a negative electrode **207**, and a separator **210** are provided in a housing **220** which is isolated from the outside, and an electrolyte solution **211** is filled in the housing **220**. In addition, the separator **210** is provided between the positive electrode **202** and the negative electrode **207**.

A first electrode **221** and a second electrode **222** are connected to a positive electrode current collector **200** and a negative electrode current collector **205**, respectively, and charge and discharge are performed by the first electrode **221** and the second electrode **222**. Moreover, there are certain gaps between a positive electrode active material layer **201** and the separator **210** and between a negative electrode active material layer **206** and the separator **210**. However, the structure is not particularly limited thereto; the positive electrode active material layer **201** may be in contact with the separator **210**, and the negative electrode active material layer **206** may be in contact with the separator **210**. Further, the lithium-ion secondary battery may be rolled into a cylinder shape with the separator **210** provided between the positive electrode **202** and the negative electrode **207**.

The positive electrode active material layer **201** is formed on the positive electrode current collector **200**. The positive electrode active material layer **201** includes a plurality of electrode materials formed in Embodiment 1. On the other hand, the negative electrode active material layer **206** is formed on the negative electrode current collector **205**. In this specification, the positive electrode active material layer **201** and the positive electrode current collector **200** on which the positive electrode active material layer **201** is formed are collectively referred to as the positive electrode **202**. The negative electrode active material layer **206** and the negative electrode current collector **205** on which the negative electrode active material layer **206** is formed are collectively referred to as the negative electrode **207**.

Note that the “active material” refers to a material that relates to insertion and extraction of ions which function as carriers and does not include a carbon layer including glucose, or the like. Thus, the conductivity of the active material refers to the conductivity of the active material itself and does not refer to the conductivity of an active material layer including a carbon layer which is formed on a surface thereof.

As the positive electrode current collector **200**, a material having high conductivity such as aluminum or stainless steel can be used. The electrode current collector **200** can have a foil shape, a plate shape, a net shape, or the like as appropriate.

In the positive electrode active material layer **201**, the positive electrode active material **100** described in Embodiment 1 which includes the core **102** containing the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$  and the covering layer **104** containing the compound represented by the general formula  $\text{LiMPO}_4$  as a main component and covering the core **102**, is included. Alternatively, the positive electrode active material **100** described in Embodiment 1 which includes the core **102** containing the compound represented by the general formula  $\text{Li}_2\text{MSiO}_4$  and the covering layer **104** containing the compound represented by the general formula  $\text{LiMPO}_4$  as a main component and covering the core **102**, and the carbon coat layer **108** which covers the positive electrode active material **100** are included. It is preferable that the solid solution material **106** exist between the core **102** and the covering layer **104**.

After the fourth heat treatment (main baking) described in Embodiment 1, the positive electrode active material **100** is ground again with the use of a ball mill machine to obtain fine powder. A conduction auxiliary agent, a binder, or a solvent is mixed into the obtained fine powder to obtain paste.

As the conduction auxiliary agent, a material which is itself an electron conductor and does not cause chemical reaction with other materials in a battery device may be used. For example, carbon-based materials such as graphite, carbon fiber, carbon black, acetylene black, and VGCF (registered trademark); metal materials such as copper, nickel, aluminum, and silver; and powder, fiber, and the like of mixtures thereof can be given. The conduction auxiliary agent is a material that assists conductivity between active materials; it is filled between active materials which are apart and makes conduction between the active materials.

As the binder, a polysaccharide such as starch, polyvinyl alcohol, carboxymethyl cellulose, hydroxypropyl cellulose, regenerated cellulose, or diacetyl cellulose; a thermoplastic resin such as polyvinyl chloride, polyvinyl pyrrolidone, polytetrafluoroethylene, polyvinylidene fluoride, polyethylene, or polypropylene; or a polymer with rubber elasticity such as ethylene-propylene-diene monomer (EPDM), sulfonated EPDM, styrene-butadiene rubber, butadiene rubber, fluorine rubber, or polyethylene oxide can be given.

The positive electrode active material **100** used as the electrode material, the conduction auxiliary agent, and the binder are mixed at 80 wt % to 96 wt %, 2 wt % to 10 wt %, and 2 wt % to 10 wt %, respectively, to be 100 wt % in total. Further, an organic solvent, the volume of which is approximately the same as that of the mixture of the electrode material, the conduction auxiliary agent, and the binder, is mixed therein and processed into a slurry state. Note that an object which is obtained by processing, into a slurry state, a mixture of the electrode material, the conduction auxiliary agent, the binder, and the organic solvent is referred to as slurry. As the solvent, N-methyl-2-pyrrolidone, lactic acid ester, or the like can be used. The proportions of the active material, the conduction auxiliary agent, and the binder are preferably adjusted as appropriate in such a manner that, for example, when the active material and the conduction auxiliary agent have low adhesiveness at the time of film formation, the amount of binder is increased, and when the resistance of the active material is high, the amount of conduction auxiliary agent is increased.

Here, an aluminum foil is used as the positive electrode current collector **200**, and the slurry is dropped thereon and is thinly spread by a casting method. Then, the slurry is further stretched by a roller press machine and the thickness is made uniform. And then, vacuum drying (under a pressure of less than or equal to 10 Pa) or heat drying (at a temperature of 150° C. to 280° C.) is performed. Thus, the positive electrode active material layer **201** is formed over the positive electrode current collector **200**. As the thickness of the positive electrode active material layer **201**, a desired thickness is selected from the range of 20 μm to 100 μm. It is preferable to adjust the thickness of the positive electrode active material layer **201** as appropriate so that cracks and separation do not occur. Further, it is preferable that cracks and separation be made not to occur on the positive electrode active material layer **201** not only when the positive electrode current collector is flat but also when the positive electrode current collector is rolled into a cylinder shape, though it depends on the form of the lithium-ion secondary battery.

As the negative electrode current collector **205**, a material having high conductivity such as copper, stainless steel, iron, or nickel can be used.

As the negative electrode active material layer **206**, lithium, aluminum, graphite, silicon, germanium, or the like is used. The negative electrode active material layer **206** may be formed on the negative electrode current collector **205** by a coating method, a sputtering method, an evaporation method, or the like. Alternatively, each material may be used alone as the negative electrode active material layer **206**. The theoretical lithium occlusion capacity is larger in germanium, silicon, lithium, and aluminum than graphite. When the occlusion capacity is large, charge and discharge can be performed sufficiently even in a small area and a function as a negative electrode can be obtained; therefore, cost reduction and miniaturization of a secondary battery can be realized. However, in the case of silicon or the like, the volume is increased approximately four times as large as the volume before lithium occlusion; therefore, it is necessary to pay attention to the risk of explosion, the probability that the material itself gets vulnerable, and the like.

As an electrolyte, an electrolyte solution that is an electrolyte in a liquid state, a solid electrolyte that is an electrolyte in a solid state may be used. The electrolyte solution contains an alkali metal ion or an alkaline earth metal ion as a carrier ion, and this carrier ion is responsible for electric conduction. Examples of the alkali metal ion include a lithium ion, a sodium ion, and potassium ion. Examples of the alkaline earth metal ion include a calcium ion, a strontium ion, and a barium ion.

The electrolyte solution **211** includes, for example, a solvent and a lithium salt or a sodium salt dissolved in the solvent. Examples of the lithium salt include lithium chloride (LiCl), lithium fluoride (LiF), lithium perchlorate (LiClO<sub>4</sub>), lithium tetrafluoroborate (LiBF<sub>4</sub>), LiAsF<sub>6</sub>, LiPF<sub>6</sub>, and Li(C<sub>2</sub>F<sub>5</sub>SO<sub>2</sub>)<sub>2</sub>N. Examples of the sodium salt include sodium chloride (NaCl), sodium fluoride (NaF), sodium perchlorate (NaClO<sub>4</sub>), and sodium fluoroborate (NaBF<sub>4</sub>).

Examples of the solvent for the electrolyte solution **211** include cyclic carbonates (e.g., ethylene carbonate (hereinafter abbreviated to EC), propylene carbonate (PC), butylene carbonate (BC), and vinylene carbonate (VC)); acyclic carbonates (e.g., dimethyl carbonate (DMC), diethyl carbonate (DEC), ethylmethyl carbonate (EMC), methylpropyl carbonate (MPC), methylisobutyl carbonate (MIBC), and dipropyl carbonate (DPC)); aliphatic carboxylic acid esters (e.g., methyl formate, methyl acetate, methyl propionate, and ethyl propionate); acyclic ethers (e.g., 1,2-dimethoxyethane (DME), 1,2-diethoxyethane (DEE), ethoxymethoxy ethane (EME), and γ-lactones such as γ-butyrolactone); cyclic ethers (e.g., tetrahydrofuran and 2-methyltetrahydrofuran); cyclic sulfones (e.g., sulfolane); alkyl phosphate ester (e.g., dimethylsulfoxide and 1,3-dioxolane, and trimethyl phosphate, triethyl phosphate, and trioctyl phosphate); and fluorides thereof. All of the above solvents can be used either alone or in combination.

As the separator **210**, paper, nonwoven fabric, a glass fiber, a synthetic fiber such as nylon (polyamide), vinylon (also called vinalon) (a polyvinyl alcohol based fiber), polyester, acrylic, polyolefin, or polyurethane, or the like may be used. However, a material which does not dissolve in the above-described electrolyte solution **211**, should be selected.

More specific examples of materials for the separator **210** are high-molecular compounds based on fluorine-based polymer, polyether such as polyethylene oxide and polypropylene oxide, polyolefin such as polyethylene and polypropylene, polyacrylonitrile, polyvinylidene chloride, polymethyl methacrylate, polymethylacrylate, polyvinyl alcohol, polymethacrylonitrile, polyvinyl acetate, polyvinylpyrrolidone, polyethyleneimine, polybutadiene, polystyrene, polyiso-

## 11

prene, and polyurethane, derivatives thereof, cellulose, paper, and nonwoven fabric, all of which can be used either alone or in combination.

When charge of the lithium-ion secondary battery described above is performed, a positive electrode terminal is connected to the first electrode **221** and a negative electrode terminal is connected to the second electrode **222**. An electron is taken away from the positive electrode **202** through the first electrode **221** and transferred to the negative electrode **207** through the second electrode **222**. In addition, a lithium ion is eluted from the active material in the positive electrode active material layer **201** from the positive electrode, reaches the negative electrode **207** through the separator **210**, and is taken in the active material in the negative electrode active material layer **206**. The lithium ion and the electron are aggregated in this region and are occluded in the negative electrode active material layer **206**. At the same time, in the positive electrode active material layer **201**, an electron is released outside from the active material, and an oxidation reaction of a metal M contained in the active material occurs.

At the time of discharge, in the negative electrode **207**, the negative electrode active material layer **206** releases lithium as an ion, and an electron is transferred to the second electrode **222**. The lithium ion passes through the separator **210**, reaches the positive electrode active material layer **201**, and is taken in the active material in the positive electrode active material layer **201**. At that time, the electron from the negative electrode **207** also reaches the positive electrode **202**, and a reduction reaction of the metal M occurs.

A lithium-ion secondary battery which is manufactured as described above includes a lithium phosphate compound having an olivine structure or a lithium silicate compound having an olivine structure as the positive electrode active material. Further, a second metal element which causes generation of carriers is added to the lithium phosphate compound or the lithium silicate compound, whereby bulk electrical conductivity is improved. Therefore, a lithium-ion secondary battery obtained in this embodiment can be a lithium-ion secondary battery with high discharge capacity, which is charged and discharged at high rate.

The structures, methods, and the like described in this embodiment can be combined as appropriate with any of the structures, methods, and the like described in the other embodiments.

## Embodiment 3

In this embodiment, an application example of the power storage device described in Embodiment 2 is described.

The power storage device described in Embodiment 2 can be used in electronic devices, e.g., cameras such as digital cameras or video cameras, digital photo frames, mobile phones (also referred to as cellular phones or cellular phone devices), portable game machines, portable information terminals, or audio reproducing devices. Further, the power storage device can be used in electric propulsion vehicles such as electric vehicles, hybrid vehicles, train vehicles, maintenance vehicles, carts, wheelchairs, and bicycles.

FIG. 3A illustrates an example of a mobile phone. In a mobile phone **410**, a display portion **412** is incorporated in a housing **411**. The housing **411** is provided with an operation button **413**, an operation button **417**, an external connection port **414**, a speaker **415**, a microphone **416**, and the like.

FIG. 3B illustrates an example of an e-book terminal. An e-book terminal **430** includes two housings, a first housing **431** and a second housing **433**, which are combined with each other with a hinge **432**. The first and second housings **431** and

## 12

**433** can be opened and closed with the hinge **432** as an axis. A first display portion **435** and a second display portion **437** are incorporated in the first housing **431** and the second housing **433**, respectively. In addition, the second housing **433** is provided with an operation button **439**, a power switch **443**, a speaker **441**, and the like.

FIG. 4 is a perspective view of an electric wheelchair **501**. The electric wheelchair **501** includes a seat **503** where a user sits down, a backrest **505** provided behind the seat **503**, a footrest **507** provided at the front of and below the seat **503**, armrests **509** provided on the left and right of the seat **503**, and a handle **511** provided above and behind the backrest **505**. A controller **513** for controlling the operation of the wheelchair is provided for one of the armrests **509**. A pair of front wheels **517** is provided at the front of and below the seat **503** through a frame **515** provided below the seat **503**, and a pair of rear wheels **519** is provided behind and below the seat **503**. The rear wheels **519** are connected to a driver portion **521** including a motor, a brake, a gear, and the like. A control portion **523** including a battery, a power controller, a control means, and the like is provided under the seat **503**. The control portion **523** is connected to the controller **513** and the driving portion **521**. The driving portion **521** is driven through the control portion **523** with the operation of the controller **513** by the user and the control portion **523** controls the operation of moving forward, moving back, turning around, and the like, and the speed of the electric wheelchair **501**.

The power storage device described in Embodiment 2 can be used in the battery of the control portion **523**. The battery of the control portion **523** can be externally charged by electric power supply using plug-in systems.

FIG. 5 illustrates an example of an electric vehicle. A power storage device **651** is provided in an electric vehicle **650**. The output of the electric power of the power storage device **651** is controlled by a control circuit **653** and the electric power is supplied to a driving device **657**. The control circuit **653** is controlled by a computer **655**.

The driving device **657** includes a DC motor or an AC motor either alone or in combination with an internal-combustion engine. The computer **655** outputs a control signal to the control circuit **653** in response to input data such as data of a driver's operation (e.g., acceleration, deceleration, or stop) and data during driving (e.g., data of an upgrade or a downgrade or data of a load on a driving wheel) of the electric vehicle **650**. The control circuit **653** adjusts the electric energy supplied from the power storage device **651** in response to the control signal of the computer **655** to control the output of the driving device **657**. In the case where the AC motor is mounted, an inverter which converts direct current into alternate current is incorporated.

The power storage device described in Embodiment 2 can be used in the battery of the power storage device **651**. The power storage device **651** can be externally charged by electric power supply using a plug-in system.

Note that in the case where the electric propulsion vehicle is a train vehicle, the battery can be charged by electric power supply from an overhead cable or a conductor rail.

This embodiment can be combined with any other embodiment.

## Embodiment 4

In this embodiment, an example in which a power storage device according to one embodiment of the present invention is used in a wireless power feeding system (hereinafter referred to as an RF power feeding system) will be described with reference to block diagrams in FIG. 6 and FIG. 7. In each

13

of the block diagrams, independent blocks show elements within a power receiving device and a power feeding device, which are classified according to their functions. However, it may be practically difficult to completely separate the elements according to their functions; in some cases, one element can involve a plurality of functions.

First, the RF power feeding system will be described with reference to FIG. 6.

A power receiving device **800** is an electronic device or an electric propulsion vehicle which is driven by electric power supplied from a power feeding device **900**, and can be applied to another object which is driven by electric power, as appropriate. Typical examples of the electronic device include cameras such as digital cameras or video cameras, digital photo frames, mobile phones (also referred to as cellular phones or cellular phone devices), portable game machines, portable information terminals, audio reproducing devices, display devices, computers, and the like. Typical examples of the electric propulsion vehicles include electric vehicles, hybrid electric vehicles, train vehicles, maintenance vehicles, carts, wheelchairs, and the like. In addition, the power feeding device **900** has a function of supplying electric power to the power receiving device **800**.

In FIG. 6, the power receiving device **800** includes a power receiving device portion **801** and a power load portion **810**. The power receiving device portion **801** includes at least a power receiving device antenna circuit **802**, a signal processing circuit **803**, and a power storage device **804**. The power feeding device **900** includes a power feeding device antenna circuit **901** and a signal processing circuit **902**.

The power receiving device antenna circuit **802** has a function of receiving a signal transmitted by the power feeding device antenna circuit **901** or transmitting a signal to the power feeding device antenna circuit **901**. The signal processing circuit **803** processes a signal received by the power receiving device antenna circuit **802** and controls charging of the power storage device **804** and supplying of electric power from the power storage device **804** to the power load portion **810**. The power load portion **810** is a driving portion which receives electric power from the power storage device **804** and drives the power receiving device **800**. Typical examples of the power load portion **810** include a motor, a driving circuit, and the like. Another power load portion can be alternatively used as appropriate. The power feeding device antenna circuit **901** has a function of transmitting a signal to the power receiving device antenna circuit **802** or receiving a signal from the power receiving device antenna circuit **802**. The signal processing circuit **902** controls operation of the power feeding device antenna circuit **901**. That is, the signal processing circuit **902** can control the intensity, the frequency, or the like of a signal transmitted by the power feeding device antenna circuit **901**.

The power storage device according to one embodiment of the present invention is used as the power storage device **804** included in the power receiving device **800** in the RF power feeding system.

With the use of the power storage device according to one embodiment of the present invention in the RF power feeding system, the amount of power storage can be larger than that in a conventional power storage device. Therefore, the time interval of the wireless power feeding can be longer (frequent power feeding is not needed).

In addition, with the use of the power storage device according to one embodiment of the present invention in the RF power feeding system, the power receiving device **800** can be formed to be compact and lightweight if the amount of power storage with which the power load portion **810** can be

14

driven is the same as that in a conventional power storage device. Therefore, the total cost can be reduced.

Next, another example of the RF power feeding system will be described with reference to FIG. 7.

In FIG. 7, the power receiving device **800** includes the power receiving device portion **801** and the power load portion **810**. The power receiving device portion **801** includes at least the power receiving device antenna circuit **802**, the signal processing circuit **803**, the power storage device **804**, a rectifier circuit **805**, a modulation circuit **806**, and a power supply circuit **807**. In addition, the power feeding device **900** includes at least the power feeding device antenna circuit **901**, the signal processing circuit **902**, a rectifier circuit **903**, a modulation circuit **904**, a demodulation circuit **905**, and an oscillator circuit **906**.

The power receiving device antenna circuit **802** has a function of receiving a signal transmitted by the power feeding device antenna circuit **901** or transmitting a signal to the power feeding device antenna circuit **901**. When the power receiving device antenna circuit **802** receives a signal transmitted by the power feeding device antenna circuit **901**, the rectifier circuit **805** has a function of generating DC voltage from the signal received by the power receiving device antenna circuit **802**. The signal processing circuit **803** has a function of processing a signal received by the power receiving device antenna circuit **802** and controlling charging of the power storage device **804** and supplying of electric power from the power storage device **804** to the power supply circuit **807**. The power supply circuit **807** has a function of converting voltage stored by the power storage device **804** into voltage needed for the power load portion. The modulation circuit **806** is used when a certain response is transmitted from the power receiving device **800** to the power feeding device **900**.

With the power supply circuit **807**, electric power supplied to the power load portion **810** can be controlled. Thus, over-voltage application to the power load portion **810** can be suppressed, and deterioration or breakdown of the power receiving device **800** can be reduced.

In addition, with the modulation circuit **806**, a signal can be transmitted from the power receiving device **800** to the power feeding device **900**. Therefore, when the amount of charged power in the power receiving device **800** is judged and the power receiving device **800** is charged with a certain amount of power, a signal is transmitted from the power receiving device **800** to the power feeding device **900** so that power feeding from the power feeding device **900** to the power receiving device **800** can be stopped. As a result, it is possible not to fully charge the power storage device **804**, so that deterioration or breakdown of the power storage device **804** due to overcharge can be reduced and the number of charge times of the power storage device **804** can be increased.

The power feeding device antenna circuit **901** has a function of transmitting a signal to the power receiving device antenna circuit **802** or receiving a signal from the power receiving device antenna circuit **802**. When a signal is transmitted to the power receiving device antenna circuit **802**, the signal processing circuit **902** generates a signal which is transmitted to the power receiving device. The oscillator circuit **906** is a circuit which generates a signal with a certain frequency. The modulation circuit **904** has a function of applying voltage to the power feeding device antenna circuit **901** on the basis of a signal generated by the signal processing circuit **902** and a signal with a certain frequency generated by the oscillator circuit **906**. Thus, a signal is output from the power feeding device antenna circuit **901**. On the other hand, when reception of a signal from the power receiving device antenna circuit **802** is performed, the rectifier circuit **903** has



15

a function of rectifying the received signal. From signals rectified by the rectifier circuit **903**, the demodulation circuit **905** extracts a signal transmitted from the power receiving device **800** to the power feeding device **900**. The signal processing circuit **902** has a function of analyzing the signal extracted by the demodulation circuit **905**.

Note that any circuit may be provided between circuits as long as the RF power feeding can be performed. For example, after the power receiving device **800** receives electromagnetic waves and the rectifier circuit **805** generates DC voltage, constant voltage may be generated by a circuit such as a DC-DC converter or a regulator. Thus, overvoltage application to the inside of the power receiving device can be suppressed.

The power storage device according to one embodiment of the present invention is used as the power storage device **804** included in the power receiving device **800** in the RF power feeding system.

With the use of the power storage device according to one embodiment of the present invention in the RF power feeding system, the amount of power storage can be larger than that in a conventional power storage device. Therefore, the time interval of the wireless power feeding can be longer (frequent power feeding is not needed).

In addition, with the use of the power storage device according to one embodiment of the present invention in the RF power feeding system, the power receiving device **800** can be formed to be compact and lightweight if the amount of power storage with which the power load portion **810** can be driven is the same as that in a conventional power storage device. Therefore, the total cost can be reduced.

Note that when the power storage device according to one embodiment of the present invention is used in the RF power feeding system and the power receiving device antenna circuit **802** and the power storage device **804** overlap with each other, it is preferable that the impedance of the power receiving device antenna circuit **802** be not changed by deformation of the power storage device **804** due to charge and discharge of the power storage device **804**. When the impedance of the antenna is changed, in some cases, electric power is not supplied sufficiently. For example, the power storage device **804** may be placed in a battery pack formed using metal or ceramics. Note that in that case, the power receiving device antenna circuit **802** and the battery pack are preferably separated from each other by several tens of micrometers or more.

In this embodiment, the charging signal has no limitation on its frequency and may have any band of frequency as long as electric power can be transmitted. For example, the charging signal may have any of an LF band of 135 kHz (long wave), an HF band of 13.56 MHz, a UHF band of 900 MHz to 1 GHz, and a microwave band of 2.45 GHz.

A signal transmission method may be selected as appropriate from various methods including an electromagnetic coupling method, an electromagnetic induction method, a resonance method, and a microwave method. In one embodiment of the present invention, in order to prevent energy loss due to foreign substances containing moisture, such as rain and mud, the electromagnetic induction method or the resonance method using a low frequency band, specifically, frequencies of a short wave of 3 MHz to 30 MHz, a medium wave of 300 kHz to 3 MHz, a long wave of 30 kHz to 300 kHz, or a very-long wave of 3 kHz to 30 kHz, may be used.

This embodiment can be combined with any other embodiment.

16

This application is based on Japanese Patent Application serial no. 2010-151742 filed with Japan Patent Office on Jul. 2, 2010, the entire contents of which are hereby incorporated by reference.

What is claimed is:

1. An electrode material comprising:

a core containing a compound represented by a general formula  $\text{Li}_2\text{ASiO}_4$  (in the general formula, A represents at least one kind of an element selected from Fe, Co, Mn, and Ni) as a main component;

a covering layer consisting essentially of a compound represented by a general formula  $\text{LiBPO}_4$  (in the general formula, B represents at least one kind of an element selected from Fe, Co, Mn, and Ni); and

a layer containing a solid solution material of  $\text{Li}_2\text{ASiO}_4$  and  $\text{LiBPO}_4$ , the layer between the core and the covering layer,

wherein the layer containing the solid solution material covers and is in contact with the core, and

wherein the covering layer covers and is in contact with the layer containing the solid solution material.

2. The electrode material according to claim 1, wherein the compound represented by the general formula  $\text{LiBPO}_4$  has high conductivity as compared to the compound represented by the general formula  $\text{Li}_2\text{ASiO}_4$ .

3. The electrode material according to claim 1, further comprising a carbon coat layer which covers the covering layer;

wherein the carbon coat layer has a thickness of greater than 0 nm and less than or equal to 100 nm.

4. The electrode material according to claim 1, wherein approximately 10% of the compound represented by the general formula  $\text{LiBPO}_4$  is dissolved in the compound represented by the general formula  $\text{Li}_2\text{ASiO}_4$  in the solid solution material.

5. A power storage device comprising:

a positive electrode, the positive electrode including a positive electrode current collector and a positive electrode active material on the positive electrode current collector; and

a negative electrode facing the positive, electrode with a separator interposed therebetween,

wherein the positive electrode active material includes an electrode material, the electrode material comprising:

a core containing a compound represented by a general formula  $\text{Li}_2\text{ASiO}_4$  (in the general formula, A represents at least one kind of an element selected from Fe, Co, Mn, and Ni) as a main component;

a layer containing a solid solution material of  $\text{Li}_2\text{ASiO}_4$  and  $\text{LiBPO}_4$ ;

a covering layer consisting essentially of a compound represented by a general formula  $\text{LiBPO}_4$  (in the general formula, B represents at least one kind, of an element selected from Fe, Co, Mn, and Ni); and

a carbon coat layer which covers the covering layer,

wherein the layer containing the solid solution material covers and is in contact with the core, and

wherein the covering layer covers and is in contact with the layer containing the solid solution material.

6. The power storage device according to claim 5, wherein the compound represented by the general formula  $\text{LiBPO}_4$  has high conductivity as compared to the compound represented by the general formula  $\text{Li}_2\text{ASiO}_4$ .

7. The power storage device according to claim 5, wherein the carbon coat layer has a thickness of greater than 0 nm and less than or equal to 100 nm.

17

8. A power storage device comprising:  
 a positive electrode, the positive electrode including a positive electrode current collector and a positive electrode active material on the positive electrode current collector; and  
 a negative electrode facing the positive electrode with a separator interposed therebetween,  
 wherein the positive electrode active material includes an electrode material, the electrode material comprising:  
 a core containing a compound represented by a general formula  $\text{Li}_2\text{ASiO}_4$  (in the general formula, A represents at least one kind of an element selected from Fe, Co, Mn, and Ni) as a main component;  
 a covering layer consisting essentially of a compound represented by a general formula  $\text{LiBPO}_4$  (in the general formula, B represents at least one kind of an element selected from Fe, Co, Mn, and Ni); and  
 a layer containing a solid solution material of  $\text{Li}_2\text{ASiO}_4$  and  $\text{LiBPO}_4$ , the layer between the core and the covering layer,  
 wherein the layer containing the solid solution material covers and is in contact with the core, and  
 wherein the covering layer covers and is in contact with the layer containing the solid solution material.
9. The power storage device according to claim 8, wherein the compound represented by the general formula  $\text{LiBPO}_4$  has high conductivity as compared to the compound represented by the general formula  $\text{Li}_2\text{ASiO}_4$ .
10. The power storage device according to claim 8, further comprising a carbon coat layer which covers the core, wherein the carbon coat layer has a thickness of greater than 0 nm and less than or equal to 100 nm.
11. The power storage device according to claim 8, wherein approximately 10% of the compound represented by the general formula  $\text{LiBPO}_4$  is dissolved in the compound represented by the general formula  $\text{Li}_2\text{ASiO}_4$  in the solid solution material.
12. The electrode material according to claim 3, wherein the core is not in contact with carbon included in the carbon coat layer.

18

13. The power storage device according to claim 5, wherein the core is not in contact with carbon included in the carbon coat layer.
14. The power storage device according to claim 10, wherein the core is not in contact with carbon included in the carbon coat layer.
15. An electrode material comprising:  
 a core containing a compound represented by a general formula  $\text{Li}_2\text{ASiO}_4$ ;  
 a layer containing a solid solution material of  $\text{Li}_2\text{ASiO}_4$  and  $\text{LiBPO}_4$ , the layer containing the solid solution material covering the core; and  
 a covering layer consisting essentially of a compound represented by a general formula  $\text{LiBPO}_4$ , the covering layer covering the layer containing the solid solution material; and  
 wherein A is at least one kind of an element selected from Fe, Co, Mn, and Ni,  
 wherein B is at least one kind of an element selected from Fe, Co, Mn, and Ni,  
 wherein the layer containing the solid solution material covers and is in contact with the core,  
 wherein the covering layer covers and is in contact with the layer containing the solid solution material, and  
 wherein the electrode material is a particle.
16. The electrode material according to claim 15, wherein the compound represented by the general formula  $\text{LiBPO}_4$  has high conductivity as compared to the compound represented by the general formula  $\text{Li}_2\text{ASiO}_4$ .
17. The electrode material according to claim 15, further comprising a carbon coat layer which covers the covering layer, wherein the carbon coat layer has a thickness of greater than 0 nm and less than or equal to 100 nm.
18. The electrode material according to claim 17, wherein the core is not in contact with carbon included in the carbon coat layer.

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